

Theory of Interplay of Nuclear Magnetism and Superconductivity in AuIn₂

M. L. Kulić^{1,2}, A.I. Buzdin², and L.N. Bulaevskii³

¹Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany

²Centre de Physique Théorique et de Modélisation, Université Bordeaux I, CNRS-URA 1537 Gradignan Cedex, France

³Los Alamos National Laboratory, Los Alamos, NM 87545 USA

(February 1, 2008)

The recently reported¹ coexistence of a magnetic order, with the critical temperature $T_M = 35 \mu\text{K}$, and superconductivity, with the critical temperature $T_S = 207 \text{ mK}$, in AuIn₂ is studied theoretically. It is shown that superconducting (S) electrons and localized nuclear magnetic moments (LM's) interact dominantly via the contact hyperfine (EX) interaction, giving rise to a spiral (or domain-like) magnetic order in superconducting phase. The electromagnetic interaction between LM's and S electrons is small compared to the EX one giving minor contribution to the formation of the oscillatory magnetic order. In clean samples ($l > \xi_0$) of AuIn₂ the oscillatory magnetic order should produce a line of nodes in the quasiparticle spectrum of S electrons giving rise to the power law behavior. The critical field $H_c(T = 0)$ in the coexistence phase is reduced by factor two with respect to its bare value.

e-mail: kulic@audrey.mpi-stuttgart.mpg.de

The problem of the coexistence of magnetic (M) order and superconductivity (S) is a long-standing one, which was first considered in 1956 theoretically by V. L. Ginzburg², and then intensively discussed after the discovery of the ternary rare earth (RE) compounds (RE)Rh₄B₄ and (RE)Mo₆X₈ (X=S,Se)^{3,4}. In many of these compounds both ferromagnetic (F) and antiferromagnetic (AF) orderings, which coexist with S, have been observed^{3,4}. It turns out that S and AF orderings coexist in several of these compounds⁵ usually down to $T = 0 \text{ K}$, while S and modified F (spiral) orderings coexist only in limited temperature interval in ErRh₄B₄, HoMo₆S₈ and HoMo₆Se₈, due to their antagonistic characters³. A general theory of magnetic superconductors has been developed in Refs. 3,6,7, where possibilities for the coexistence of S and spiral or domain-like magnetic order (which is the modified F order in the presence of superconductivity) have been elaborated quantitatively by including the exchange and electromagnetic interaction of superconducting electrons and localized magnetic moments (LM's). To the similar conclusion came also Blount and Varma⁸ by taking into account the electromagnetic interaction only. Note, that some heavy fermions UPt₃, URu₂Si₂ etc. show the coexistence of the AF and S orderings, while S and oscillatory M order coexist in quaternary intermetallic compounds (RE)Ni₂B₂C, see Ref. 9.

However, until recently it was impossible to investigate the interplay of S and nuclear magnetic order, because of lack of suitable materials. Thanks to the pioneering work on superconductivity and magnetism at ultra-low temperatures by Pobel's group in Germany^{1,10-12}, as well as of Lounasmaa's one in Finland^{13,14}, at least two materials were discovered where S and nuclear M order seem to coexist. The first one is metallic Rh, which is superconducting at $T_S = 325 \mu\text{K}$ and whose nuclear moments might be ordered antiferromagnetically at $T_N \sim 1 \text{ nK}$, see Refs. 15,16. There are also some hints on the AF

order at negative nuclear temperature T_n . Rh is an interesting system because of its rather large Korringa constant $\kappa (\equiv \tau_1 T_e) \leq 10 \text{ s}\cdot\text{K}$, where τ_1 is the spin-lattice relaxation time and T_e is the electronic temperature. Large κ (or τ_1) in Rh allows to achieve very low nuclear temperatures $T_n \ll T_e$, as well as a realization of negative T_n . The problem of the competition of nuclear magnetism and S order in Rh will be studied elsewhere.

A remarkable achievement in this field was recently done by Pobel's group by investigating AuIn₂, where the coexistence of the nuclear ferromagnetism and superconductivity ($T_S = 207 \text{ mK}$) was found^{10,11} below $T_M = 35 \mu\text{K}$. Because of good thermal coupling of nuclear magnetic moments to the conduction electrons in AuIn₂ (Korringa constant $\kappa = 0.1 \text{ s}\cdot\text{K}$) the experiments were performed in thermal equilibrium $T_n = T_e$ down to $T = 25 \mu\text{K}$. It was also found that AuIn₂ is a type-I superconductor with the bare critical field $H_{c0}(T = 0) = 14.5 \text{ G}$, which would be in absence of the F ordering, while in its presence $H_c(T)$ is decreased, i.e. $H_c = 8.7 \text{ G}$ at $T = 25 \mu\text{K}$. The latter result is a hint that S and F orderings might coexist in the bulk down to $T = 0$.

In the following the coexistence of S and M order in AuIn₂ is studied in the framework of the microscopic theory of magnetic superconductors^{3,6}. It considers interactions between LM's and conduction electrons: a) via the direct hyperfine interaction – because of simplicity it is called the *exchange* (EX) one; b) via the dipolar magnetic field $\mathbf{B}_m(\mathbf{r}) = 4\pi\mathbf{M}(\mathbf{r})$, which is created by LM's, it is called *electromagnetic* (EM) interaction. The general Hamiltonian which describes conducting electrons and nuclei moments in AuIn₂ is given by

$$\hat{H} = \int d^3r \{ \psi^\dagger(\mathbf{r}) \epsilon (\hat{\mathbf{p}} - \frac{e}{c} \mathbf{A}) \psi(\mathbf{r}) + [\Delta(\mathbf{r}) \psi^\dagger(\mathbf{r}) i \sigma_y \psi^\dagger(\mathbf{r}) + \text{c.c.}] + \frac{|\Delta(\mathbf{r})|^2}{V} + \sum_i J_{en} \delta(\mathbf{r} - \mathbf{r}_i) \psi^\dagger(\mathbf{r}) \sigma \mathbf{I}_i \psi(\mathbf{r}) \}$$

$$+\frac{[\text{curl}\mathbf{A}(\mathbf{r})]^2}{8\pi}\} + \sum_i [-\mathbf{B}(\mathbf{r}_i)g_n\mu_n\mathbf{I}_i + \hat{H}_a(\mathbf{I}_i)] + \hat{H}_{imp}. \quad (1)$$

Here, $\epsilon(\mathbf{p})$, $\Delta(\mathbf{r})$, \mathbf{A} , $J_{en}(\mathbf{r})$ and V are the quasiparticle energy, the superconducting order parameter, the vector potential, the hyperfine contact coupling between electronic spins σ (Pauli matrices) and localized nuclear moments (LM's) \mathbf{I}_i and the electron-phonon coupling constant respectively. The first three terms in Eq. (1) describe the superconducting mean-field Hamiltonian in the magnetic field $\mathbf{B}(\mathbf{r}) = \text{curl}\mathbf{A}(\mathbf{r})$ due to LM's and screening current, while the term \hat{H}_{imp} describes the electron scattering (including also the spin-orbit one) on nonmagnetic impurities. The term $-\mathbf{B}(\mathbf{r}_i)g_n\mu_n\mathbf{I}_i$ describes the dipole-dipole interaction of LM's, as well as their interaction with the magnetic field due to screening superconducting current – see more below. $\hat{H}_a(\mathbf{I}_i)$ is (together with the dipole-dipole interaction) responsible for magnetic anisotropy of LM's. In the case of AuIn₂, which is simple cubic crystal, its form is unknown – see discussion below. Later we show that under experimental conditions reported in Refs. 1,10,11 the ferromagnetic structure, which would be in absence of S order, is transformed in the presence of superconductivity into spiral (or domain-like) one – depending on magnetic anisotropy.

A. The characteristic parameters of AuIn₂

The magnetic critical temperature $T_M=35\text{ }\mu\text{K}$ is very small compared to $T_S \approx 0.2\text{ K}$, and it is much larger than the characteristic dipole-dipole temperature $\Theta_{em}(\approx 1\text{ }\mu\text{K})$, see below. This fact allows us to estimate the hyperfine contact interaction between electrons and LM's, which is characterized by the parameter $h_{ex} = J_{en}(0)n_m |\langle \mathbf{I}_i \rangle|$, where n_m is the concentration of LM's. The indirect exchange energy (via conduction electrons) between the LM's of nuclei is characterized by the RKKY temperature $\Theta_{ex} = N(0)h_{ex}^2/n_m$, where $N(0)$ is the electronic density of states at the Fermi level. The crystallographic structure gives $n_m \approx 3 \times 10^{22}\text{ cm}^{-3}$. $N(0)$ is obtained by knowing $H_{c0}(T=0) = 14.5\text{ G}$, see Refs. 1,10, which gives $N(0) \approx 0.64 \times 10^{34}\text{ erg}^{-1}\text{cm}^{-3}$. Since $T_M(=35\text{ }\mu\text{K})$ is predominantly due to the indirect exchange interaction between In nuclei moments one has $T_M \approx \Theta_{ex}$, which gives $h_{ex} \approx 1\text{ K}$. Note that one has $h_{ex} > \Delta_0(\approx 0.36\text{ K})$, which gives rise to a gapless quasiparticle spectrum in S state below T_M in clean samples ($l > \xi_0$) of AuIn₂, see below.

The electromagnetic (EM) dipole-dipole interaction between LM's is characterized by $\Theta_{em} = 2\pi n_m \mu^2$, where $\mu = g_n \mu_n I$. In case of the In nuclei in the AuIn₂ cubic crystal one has $\mu \simeq 5.5\mu_n$, i.e. $\Theta_{em} \approx 1.2\text{ }\mu\text{K}$ ($\ll T_M$), which means that the dipole-dipole interaction does not contribute to T_M in AuIn₂. However, it makes the magnetic structure transverse in S state, see below.

From $\Delta_0(\simeq 1.76\text{ }T_S)$ and $v_F \approx 1.68 \times 10^8\text{ cm/s}$ ^{10,11} one gets $\xi_0 \simeq 10^5\text{ }\text{\AA}$, while from the resistivity measurements^{1,11}, where RRR=500, one obtains $l \approx 3.6 \times 10^4\text{ }\text{\AA}$. Accordingly, the spin-orbit scattering mean-free path is very large, i.e. $l_{so} > 3.6 \times 10^4\text{ }\text{\AA}$, because

one always has $l_{so} > l$. Note that $l < \xi_0$ and the system is in the dirty (but not very dirty) limit. The London penetration depth $\lambda_L \approx 200\text{ }\text{\AA}$ is estimated from H_{c0} and by knowing ξ_0 and l , which means that AuIn₂ is the type I superconductor at temperatures where S and M orderings coexist. From the above analysis we estimate the parameter $(h_{ex}\tau/\hbar)^2 = 0.1$. It is small and dirty limit may be used to treat effect of exchange field on superconductivity. This simplifies the theoretical analysis given below. Here $\tau = l/v_F$ is the electron scattering time.

B. Theoretical analysis of AuIn₂

It was shown in Refs. 3,6,17 that when the electron spin-orbit interaction is weak, i.e. when $l_{so}/l \gg (k_F^{-1}\xi_0/l^2)^{2/3}$, there is a peak in the spin susceptibility in the superconducting state at nonzero wave vector Q . This means that in the superconducting state an oscillatory magnetic order is more favorable than the F one. In AuIn₂ one has $k_F = 1.45\text{ }\text{\AA}^{-1}$ and thus the condition for an oscillatory magnetic order is $l_{so} \gg 10^{-2}l$. Since by definition $l_{so} > l$ we see that the spin-orbit interaction does not play any role in the formation of the magnetic structure in the coexistence phase of AuIn₂. The magnetic order can be a spiral or domain-like one, depending on the magnetic anisotropy, see below. The problem is now reduced to the study of electrons moving in an oscillatory (with the wave vector \mathbf{Q}) exchange and magnetic field $\mathbf{h}_{ex}(\mathbf{R}) = h_{ex}\mathbf{S}(\mathbf{R})$, $\mathbf{B}(\mathbf{R}) = \text{curl}\mathbf{A}(\mathbf{R})$ respectively. By using the Eilenberger equations for the normal $g_\omega(\mathbf{v}, \mathbf{R})$ and anomalous $f_\omega(\mathbf{v}, \mathbf{R})$ electronic Green's function, where the superconducting order parameter $\Delta(\mathbf{R})$ is a solution of the self-consistency equation $\Delta(\mathbf{R}) = 2\pi g \sum_\omega \int d\mathbf{n} f_\omega(\mathbf{R}, \mathbf{n})/4\pi$ ($g = N(0)V$ is the electron-phonon coupling constant) one obtains the free-energy functional of the system $F_{SM}\{\Delta, \mathbf{S}_Q, \mathbf{Q}\}$. It may be presented as a sum of magnetic (F_M), superconducting (F_S) and interacting (F_{int}) parts, i.e. $F_{SM}\{\Delta, \mathbf{S}(\mathbf{R})\} = F_S\{\Delta\} + F_M\{\mathbf{S}_Q, \mathbf{Q}\} + F_{int}\{\Delta, \mathbf{S}_Q, \mathbf{Q}\}$. By assuming that: a) $\pi E_S/F_{int} > 1$, $E_S = N(0)\Delta^2/2n_m$ – this is indeed fulfilled in AuIn₂, where $\pi E_S/F_{int} \sim 100$, and b) the Fermi surface is isotropic – it is also fulfilled in AuIn₂, one gets the free-energy F_{SM}

$$F_S\{\Delta\} = -\frac{1}{2}N(0)\Delta^2 \ln \frac{e\Delta_0^2}{\Delta^2}, \quad (2)$$

$$F_{int} = F_{int}^{ex} + F_{int}^{em} = F_{int}^{ex} + \sum_{\mathbf{Q}} \frac{3\pi^2\Theta_{em}\Delta |\mathbf{S}_{Q,\perp}|^2}{v_F Q (\lambda_L Q)^2}.$$

Here the terms F_{int}^{ex} and F_{int}^{em} in Eq. (2) describe the exchange EX and EM interaction of superconducting electrons with LM's respectively. F_{int}^{ex} , and F_M depend on h_{ex} , \mathbf{S}_Q , l , ξ_0 etc. We consider only those cases which might be important for the physics of AuIn₂.

1. Dirty case ($l < \xi_0$). This case is *realized* in AuIn₂ as reported in Refs. 1,10, where $l \approx 3.6 \times 10^4\text{ }\text{\AA}$ and $\xi_0 \approx 10^5\text{ }\text{\AA}$. Immediately below the magnetic critical temperature

$T_M = 35 \mu\text{K}$ the magnetization is small and F_M has the form

$$F_M = \sum_{\mathbf{Q}} \{ -\Theta_{ex} \chi_m^{-1}(Q) [|\mathbf{S}_{Q,\perp}|^2 + |\mathbf{S}_{Q,\parallel}|^2] + \Theta_{em} |\mathbf{S}_{Q,\parallel}|^2 \} + F_0 + F_a \quad (3)$$

where $\mathbf{Q} \cdot \mathbf{S}_Q = Q S_{Q,\parallel}$ and $\chi_m^{-1}(T, Q) = (T - \Theta_{ex})/\Theta_{ex} + Q^2/12k_F^2$. Here, $k_F = 1.45 \text{ \AA}^{-1}$ is the Fermi wave vector. The isotropic term $F_0 \{ \mathbf{S}_Q^2 \}$ (per LM) describes higher order terms in \mathbf{S}_Q^2 , while F_a (per LM) describes magnetic anisotropy of the system, see discussion below.

Since the sample of AuIn₂ is in dirty limit¹ – it holds also $Ql \gg 1$, see below, $(h_{ex}\tau/\hbar)^2 \approx 0.1 \ll 1$, the mean-free path drops out from the term F_{int}^{ex} in Eq. (2). Since we consider the spiral (helical) structure with the amplitude S_Q , which contains only one harmonic Q . Then the sum over \mathbf{Q} in Eqs. (2),(3) drops out and one obtains $F_{int}^{ex} = \pi\Delta \cdot S_Q^2 \Theta_{ex}/2v_F Q$. By minimizing $F_{SM}\{\Delta, S_Q, Q\}$ with respect to Δ, S_Q and Q one gets the *spiral* magnetic structure at T very near T_M with the wave vector $Q_S = (3\pi k_F^2/\xi_0)^{1/3} \approx 5 \times 10^{-2} \text{ \AA}^{-1}$ and the period is $L_S = 2\pi/Q_S \approx 120 \text{ \AA}$ – see Fig.1a. Note, one has $Q_S l \sim 10^3$, i.e. the required theoretical condition $Ql \gg 1$ is fulfilled in AuIn₂. In this case the EM interaction in Eq. (2) is negligible, i.e. $F_{int}^{em}/F_{int}^{ex} \approx (\Theta_{em}/\Theta_{ex} \lambda_L^2 Q^2) < 10^{-2}$ and the spiral magnetic structure is due to the effective EX interaction between electrons and LM's (of In nuclei) mainly. However, the magnetic dipole-dipole interaction between In nuclei, although small ($\Theta_{em} \ll \Theta_{ex}$), makes the structure transverse ($\mathbf{Q} \cdot \mathbf{S}_Q = 0$) due to the term $\Theta_{em} |\mathbf{S}_{Q,\parallel}|^2$ in Eq. (3).

On cooling, S_Q^2 grows and higher order terms of S_Q^2 must be included in F_M as well as magnetic anisotropy F_a . However, in AuIn₂, which is simple cubic structure, only higher order terms contribute to F_a (per LM), i.e. $F_a = D(S_x^4 + S_y^4 + S_z^4)$. One expects that $D < \Theta_{em}$ (or more realistic $D \ll \Theta_{em}$, see below). However, if D fulfills the condition $(D/\Theta_{ex})^{3/4} > 0.25(k_F \xi_0)^{-1/2}$ (one should have $D/\Theta_{ex} > 10^{-3}$ in the case of AuIn₂) the spiral structure is transformed into a striped one-dimensional transverse domain structure^{3,6} – see Fig.1b. The condition on D means that the domain-wall thickness should be much smaller than the period of the domain structure. The magnetic energy (per LM's) in the case of the domain magnetic structure is given by $F_M = F_0(S_Q^2) - \Theta_{ex} S_Q^2 + \eta(S_Q^2, T)Q/\pi$, where $F_0(S_Q^2)$ contains terms of higher order in S_Q^2 . Here $\eta = k_F^{-1} \Theta_w S_Q^2$ is the surface energy of the domain wall, and $\Theta_w \approx 0.58(\Theta_{ex} D)^{1/2}$ in the case of rotating Bloch wall (where $D \ll \Theta_{ex}$). The wave vector of the domain structure Q_D , obtained by minimizing F_{SM} , at $T \ll T_M$ is given by $Q_D \approx 2(\Theta_{ex}/\Theta_w k_F \xi_0)^{1/2}$. Note, the wave vector of the domain structure Q_D is smaller than Q_S for the spiral. Because of the simple cubic structure of AuIn₂ it is more probable that $D/\Theta_{ex} < 10^{-3}$ than opposite,

which means that AuIn₂ is the strong candidate to be the first system where superconductivity coexists with *spiral* magnetic order down to $T = 0$, see below. Namely, it turns out that at $T = 0$ the magnetic energy per LM is $F_M \approx -\Theta_{ex} = -35 \mu\text{K}$, while the superconducting energy per LM is $F_S \approx -4 \mu\text{K}$. However, the interaction energy (per LM) is very small, $F_{int} \ll 10^{-2} \mu\text{K}$. This result means that even at $T = 0$ the loss of energy due to the interaction, F_{int} , is much smaller than the gain due to the condensation energy F_S , i.e. $F_S + F_{int} \approx F_S < 0$, and the oscillatory magnetic structure and S order coexist in AuIn₂ down to $T = 0$.

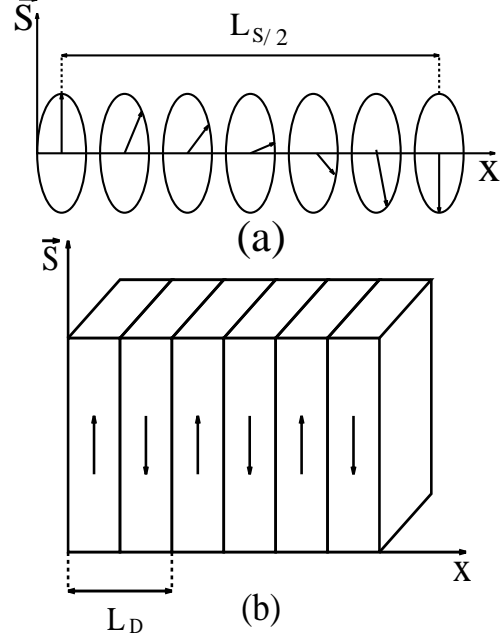


FIG. 1. (a) The spiral magnetic structure $\mathbf{S}(x)$, with the period L_S in the superconducting phase for small anisotropy $D/\Theta_{ex} < 10^{-3}$. (b) The domain-like magnetic structure $\mathbf{S}(x)$, with the period L_D in the superconducting phase for appreciable anisotropy $D/\Theta_{ex} > 10^{-3}$.

2. Clean limit ($l > \xi_0$). The present experiments were performed on dirty (but not very dirty) AuIn₂ samples, where $l < \xi_0$. In that case the motion of Cooper pairs in the coexistence phase is diffusive and there is an isotropization of the quasiparticle spectrum. This means that the oscillatory magnetic structure acts like magnetic impurities – for similarity and differences of effects of magnetic impurities and the oscillatory magnetic structure see Ref. 3. However, it would be interesting to perform experiments on clean AuIn₂ samples with $l > \xi_0$ – for instance on samples with a residual resistivity ratio $\text{RRR} > 1500$. Namely, it was shown in Refs. 3,7 that the oscillatory magnetic order in clean superconductors can give rise to the gapless quasiparticle spectrum with nodes on a line at the Fermi surface if $h_{ex} > \Delta_0$. This is just the case in AuIn₂, where $h_{ex} \approx 1 \text{ K}$ and $\Delta_0 \approx 0.36 \text{ K}$. In the clean limit the quasiparticle motion is anisotropic in the presence of an oscillatory magnetic structure with the wave vector \mathbf{Q} , and the

quasiparticle energy vanishes on lines at the Fermi surface given by $\mathbf{v}_F \cdot \mathbf{Q} = 0$ if $h(T) = h_{ex} S_Q(T) > \Delta_0$, see Ref. 3. In this case the density of states for $E < \Delta_0$ is $N_s(E) = N(0)(\pi E h / \Delta_0 v_F Q_d) \ln(4\Delta_0 / \pi E)$ for the domain structure and $N_s(E) = N(0)(\pi E h / \Delta_0 v_F Q_d)$ for the spiral one. $N_s(E)$ can be experimentally obtained by measuring voltage dependence of the tunneling conductivity in the S-N junction with AuIn₂ being in the coexistence phase.

C. Effect of magnetic field

Because of very small interaction energy one expects that the critical field $H_c(T)$ does not vanish down to $T = 0$. Indeed, equating Gibbs energy for superconducting state and that of normal ferromagnetic state one gets

$$F_S + F_M + F_{int} = F_M^0 - \frac{H_c^2}{8\pi} - \mathbf{M} \cdot \mathbf{H}_c, \quad (4)$$

and if one defines $H_{SM} \equiv [8\pi(F_M^0 - F_M - F_S - F_{int})]^{1/2}$

$$H_c = \sqrt{H_{SM}^2 + (4\pi M_0)^2} - 4\pi M. \quad (5)$$

At $T \ll T_M$ the magnetization \mathbf{M} is saturated, i.e. $M \approx M_0 = 5.5 n_m \mu_n$. Because $F_{int} \ll F_S, F_M$ one has small difference in magnetic energy of oscillatory state, F_M and that of ferromagnetic state, F_M^0 . As result, $H_{SM} \approx H_{c0}(0) = [8\pi(-F_S^0)]^{1/2}$. The experimental values¹ are $H_{c0}(0) \approx 14.5$ G and $4\pi M_0 \approx 11$ G which gives $H_c(0) \approx 7$ G. It was found experimentally¹ that $H_c \approx 8.7$ G at $T = 25$ μ K, and thus our estimate is reasonable. Nonzero value of $H_c(0)$ in AuIn₂ is in a contrast to the case of magnetic type II superconductors ErRh₄B₄ and HoMo₆S₈, where $H_c(T)$ tends to zero [as well as $H_{c2}(T)$] at $T \rightarrow T_M$, because in these compounds one has $F_{int} \approx |F_N - F_S|$ near some temperature $T_{S2} < T_M$. At $T > T_M$ one obtains $H_c = H_c^0 / (1 + 4\pi\chi_M)$ in absence of demagnetization effects, where $\chi_M(T) = \bar{\Theta}_{em} / (T - \Theta_{ex})$ and $\bar{\Theta}_{em} = \Theta_{em} / 6\pi$. The change of the slope of $H_c(T)$ takes place at T very near T_M . The experimental broadening of the transition in the magnetic field can be due to the polycrystallinity of the sample, where even small magnetic anisotropy of the crystallites can produce percolation-like broadened resistive transition in magnetic field^{18,19}.

In conclusion, we found, that superconductivity coexists with a domain-like magnetic structure if the anisotropy parameter D is not too small, i.e. $D/\Theta_{ex} > 10^{-3}$. We estimate the period $L_D \approx 300$ \AA for $D \sim 1$ μ K. In the opposite case, $D/\Theta_{ex} < 10^{-3}$, the magnetic structure is spiral with the period $L_S \approx 120$ \AA . The realization of the spiral structure in AuIn₂ is more probable due to the simple cubic structure of this compound and accordingly due to small magnetic anisotropy.

It is also proposed that in the case of very clean AuIn₂ samples with $RRR > 1500$ there is a line, given by $\mathbf{v}_F \cdot \mathbf{Q} = 0$, at the Fermi surface with nodes in the quasiparticle spectrum in the coexistence phase. It would

be interesting to study this regime experimentally, because in that case thermodynamic and transport properties show power law behavior.

We would like to devote this paper to the pioneer in the field of magnetic superconductors Vitalii Lazarevich Ginzburg on the occasion of his 80-th anniversary. M.L.K. acknowledges Universit  Bordeaux for kund hospitality and O. Andersen, L. Hedin, H.-U. Habermeyer, C. Irslinger, Y. Leroyer, M. Mehring, K.-D. Schotte and V.S. Oudovenko for support.

-
- ¹ S. Rehmann, T. Hermannsd rfer and F. Pobel, Phys. Rev. Lett. **78**, 1122 (1997).
 - ² V.L. Ginzburg, Zh. Eksp. Teor. Fiz. **31**, 202 (1956).
 - ³ L.N. Bulaevskii, A.I. Buzdin, M.L. Kuli  and S.V. Panyukov, Adv. Phys., **34**, 175 (1985); Sov. Phys. Uspekhi **27**, 927 (1984).
 - ⁴ M.B. Maple, H.C. Hammaker and L.D. Woolf, in *Superconductivity in Ternary Compounds II, Topics in Current Physics*, ed. M.B. Maple and  . Fischer, Springer Verlag, v. 34, (1982).
 - ⁵ A.I. Buzdin, L.N. Bulaevskii, Sov. Phys. Uspekhi **29**, 412, (1986).
 - ⁶ L.N. Bulaevskii, A.I. Buzdin, M.L. Kuli  and S.V. Panyukov, Phys. Rev. B **28**, 1370 (1983).
 - ⁷ L.N. Bulaevskii, M.L. Kuli  and A.I. Rusinov, Solid State Comm., **30**, 59 (1979); J. Low Temp. Phys., **39**, 256 (1980).
 - ⁸ E.I. Blount and C.M. Varma, Phys. Rev. Lett. **42**, 1079 (1979).
 - ⁹ L.J. Chang, C.V. Tomy, D.M. Paul and C. Ritter, Phys. Rev. B **54**, 9031 (1996).
 - ¹⁰ T. Hermannsd rfer and F. Pobel, J. Low Temp. Phys., **100**, 253 (1995).
 - ¹¹ T. Hermannsd rfer, P. Smeibidl, B. Schr der-Smeibidl and F. Pobel, Phys. Rev. Lett. **74**, 1665 (1995).
 - ¹² F. Pobel, Physics Today, January 1993; Physikalische Bl tter, **50**, 853 (1994); Physica B **197**, 115 (1994).
 - ¹³ O.V. Lounasmaa, Physics Today, October 1989; P. Hakonen and O.V. Lounasmaa, Science **265**, September 1994; P. Hakonen, O.V. Lounasmaa and A. Oja, J. Magn. and Magn. Mat. **100**, 394 (1991).
 - ¹⁴ A.S. Oja and O.V. Lounasmaa, Rev. Mod. Phys., **69**, 1 (1997).
 - ¹⁵ Ch. Buchal, F. Pobel, R.M. Mueller, M. Kubota and J.R. Owers-Bradley, Phys. Rev. Lett. **50**, 64 (1983).
 - ¹⁶ P.J. Hakonen, R.T. Vuorinen, and J.E. Martikainen, Phys. Rev. Lett. **70**, 2818 (1993).
 - ¹⁷ M. Kaufman and O. Entin-Wohlman, Physica, **B69**, 77 (1976).
 - ¹⁸ L.N. Bulaevskii, A.I. Buzdin, M.L. Kuli , Solid State Com., **41**, 309 (1981); Phys. Lett. A **85**, 169 (1981).
 - ¹⁹ A.I. Buzdin and L.N. Bulaevskii, Fiz. Nizkih, Temp. **6**, 1528 (1980).